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PRELIMINARY DATA ON LUNAR SOIL COLLECTED BY THE "LUNA-20" AUTOMATIC STATION

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PRELIMINARY DATA ON LUNAR SOIL COLLECTED BY THE "LUNA-20" AUTOMATIC STATION[1]

A.P. Vinogradov[2]

ABSTRACT. Examination of rock samples collected by the "Luna-20" automatic space station has revealed considerable differences between the continental and mare rock formations on the Moon, especially in regard to iron.

The "Luna-20" Automatic Station landed in a typical continental region of the Moon at 2219 Moscow time on 21 February 1972; on 23 February it drilled into the surface and collected a soil sample. The landing site is located between and Mare Fecunditatis and Mare Crisium at a point having the coordinates 3° 32 minutes N and 56° 33 minutes E, approximately 35 to 40 km from the northern shore of Mare Fecunditatis. The landing site of the "Luna-20" Automatic Station is 120 km due north of the landing site of the "Luna-16." The boundary between the Mare and the continent is located nearly halfway between these two points (Figure 1). The nature of the coastline is indicative of a comparitively quiet subsidence of Mare Fecunditatis, complicated by numerous faults running across the continent. The material composing the continent, whose elevation in the area where the sample was collected reaches 1 km, is unquestionably older than the lava flows which fill the Mare and cannot contain a significant amount of Mare material. /*763

The relief of the landing area is typical of the continental regions of the Moon. It is basically composed of areas with gently hilly relief,

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*Numbers in the margin indicate pagination in the foreign text.

combined with ridge-like uplifts, scarps and irregular depressions. These formations are dotted by numerous craters ranging in diameter up to several tens of kilometers. The density of the distribution of craters larger than 3 km in diameter is approximately 50 times greater than the density of craters of similar size in the northern part of Mare Fecunditatis.

Several kilometers to the east of the landing site is the rim of the wall of the crater Apollonius C, which has a diameter of approximately 10 km and a depth of slightly more than 1 km. Judging by the degree of prominence in the relief of "Apollonius C", this crater is comparitively young (possibly Copernican) and the ejecta from this crater may play an important role in the composition of the soil collected by the "Luna-20" station.

In the immediate vicinity of the station, the surface is relatively flat and has a gently rolling appearance. The lengths of the slopes of the hills may vary from hundreds of meters to several kilometers. Judging by the pictures that were obtained, the station landed on the eastern slope of one of these hills, with an 8-10° slope. There are a few craters on this surface with gentle slopes, 0.5 to 1 meter in diameter, and numerous stones with a maximum diameter of 1-3 cm.

The design of the drill of the "Luna-20" is similar to that used aboard the "Luna-16" station. A container with the drill containing the soil was housed in a helium chamber and the soil was placed on a tray, as shown in Figure 2. /764

The soil or regolith from the "Luna-20" is a friable inequigranular material, light in color, much brighter than the regolith from Mare Fecunditatis ("Luna-16"). Even the very first examination of the regolith from "Luna-20" showed that in comparison with the regolith from "Luna-16" it contains much less molten particles, spheriods, etc., which created a pronounced mirror-like effect in the regolith from Mare Fecunditatis. The regolith from the continental region of the Moon also displays a pronounced ability for electrostatic charging. The bulk weight of the regolith from "Luna-20" was 1.1 to 1.2 g/cm^2. It can be readily compacted to 1.7 to 1.8 g/cm^2. On the basis of a granulometric analysis, the average particle size in the regolith is approximately 70-80 microns. There are more large particles measuring more than 1 mm in it than in the soil from "Luna-16" (Figures 3 and 4). The brighter color of the regolith from "Luna-20" was supported by comparative studies of the albedo. The albedo value is much higher than for the albedo of the regolith from the "Luna-16", "Apollo 11", and "Apollo 12". For a fine fraction (- 0.083), for the ultraviolet region is equal to 0.145, for the visable region 0.200. and for the near infrared it is 0.260. The maximum diffuse reflection is obtained at λ = 4 microns and is equal to 0.370 (Figure 5). The IR-spectra of various fractions of the regolith from "Luna-20" show a number of bands which are, on the whole, characteristic of more crystalline formations than are the spectra from the samples of regolith collected by "Luna-16", "Apollo 11", and "Apollo 12". The IR-spectrum of the regolith from "Luna-20" is very similar to the spectrum of the terrestrial anorthite An_{100}, but is characterized by a slightly different shape of the bands. Annealing (up to 1,000°C in argon) makes the spectrum more pronounced, but no new bands appear (in contrast to the regolith from "Luna-16", "Apollo 11", and "Apollo 12").

A microscopic examination of the regolith from "Luna-20" revealed a marked difference from the Mare regolith collected by "Luna-16", "Apollo 11", and "Apollo 12". Lumps of crystalline rock and minerals with well-preserved boundaries and cleavage faces predominate in the regolith (Figure 6); very few slagged breccias and spheriods, characteristic of regolith from lunar maria, are seen. A large portion of the particles are composed of anorthositic rocks, composed to a large degree of feldspar (plagioclase). Among them, one can find completely crystalline particles belonging primarily to anorthosites, and particles of rock with the same composition but with an effusive appearance. There are also individual grains of plagioclase which are found in all granulometric classes of regolith. The largest of them evidently constitute material made up of fragmented large-crystalline anorthosite. It is also necessary to mention in this context the presence of rocks that can be classed as troctolites, composed primarily of feldspar and olivine. It is evident from Figure 7 that the position of ilmenite in the "Luna-20" regolith was occupied by ulvospinels. In contrast to the regolith from the lunar maria, the rocks of basalt type are generally composed of a few particles of basalt

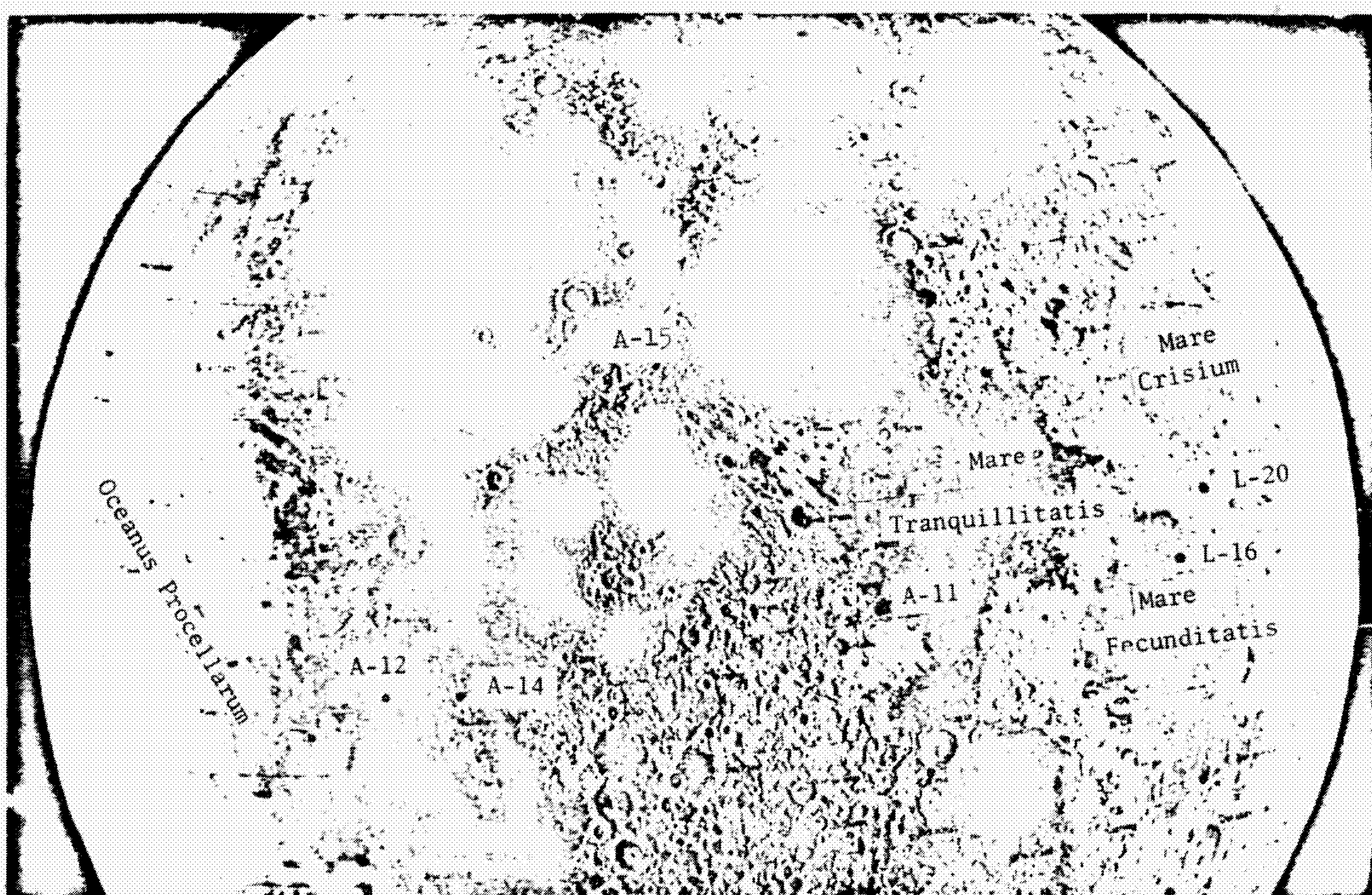

Figure 1. Map of the Moon with Landing Sites of the "Luna-16" and "Luna-20" Stations and the Apollo 11, 12, 14, 15, and 16 Spacecraft.

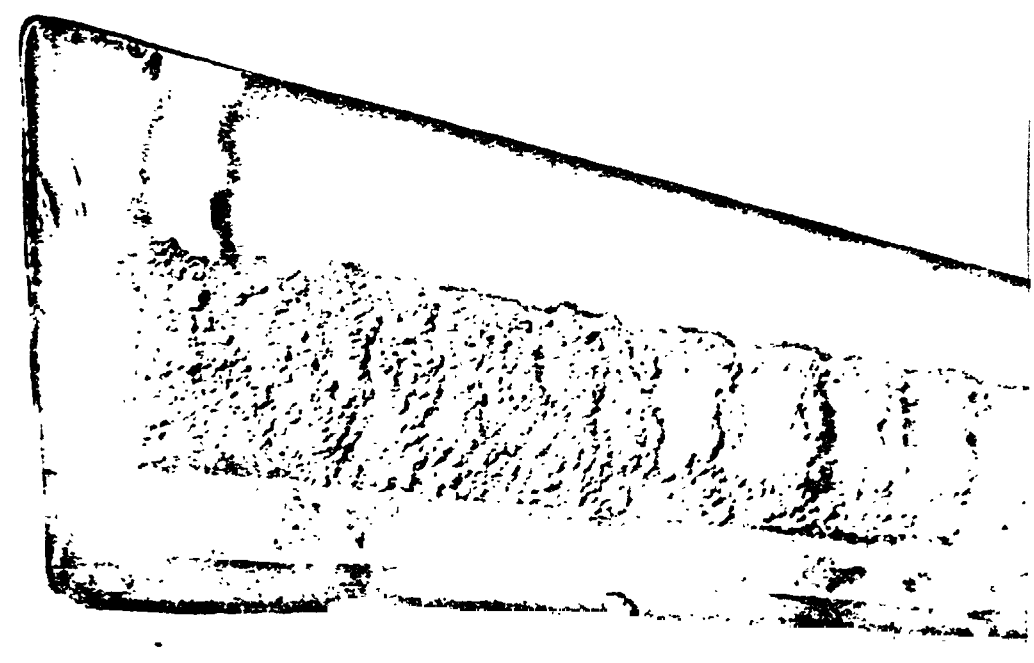

Figure 2. Soil on Tray in Receiving Helium Chamber.

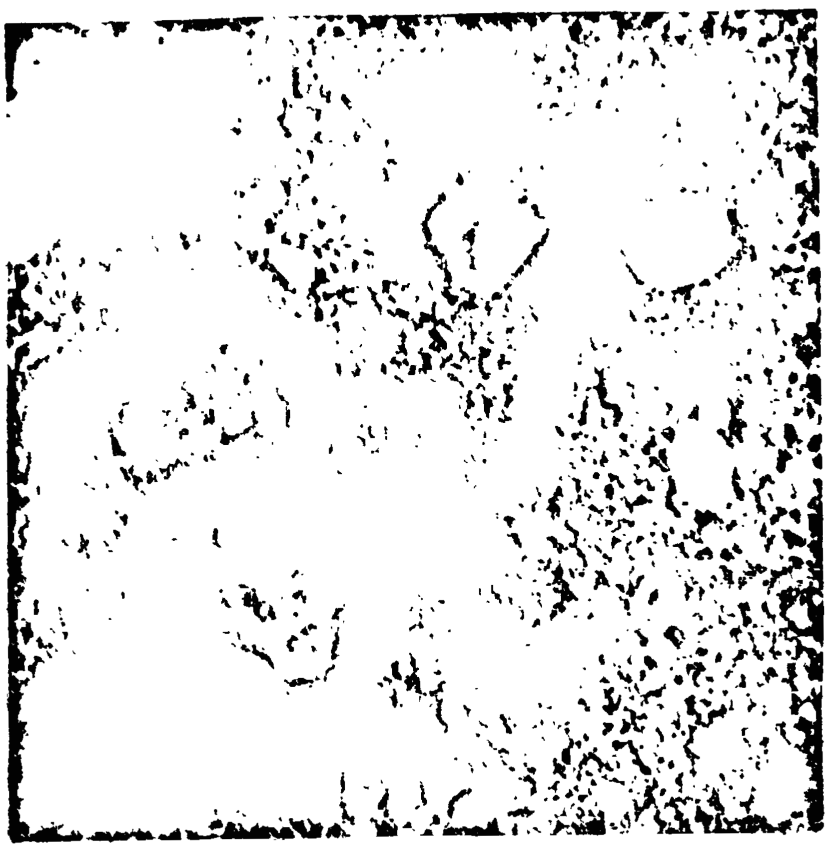

Figure 3. Individual Portions of Regolith.

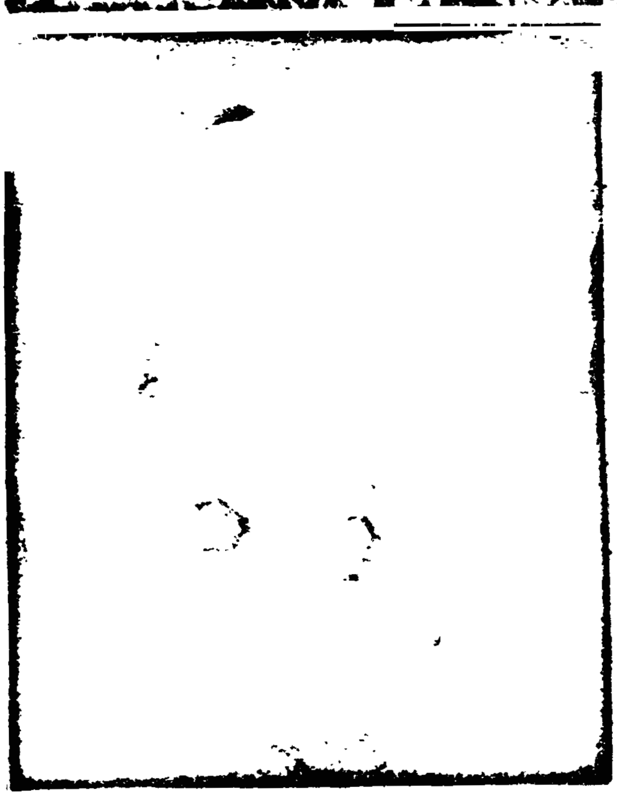

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Figure 4. Fragment of Anorthositic Rock Containing Spherical Pores and Small Inclusions of Metallic Iron. Fraction - 0.9 mm; 30 X.

completely analogous to the basalts of lunar maria. The same particles of gabbro and peridotite rock are found in small amounts. Pyroxenes are found with predominance of orthopyroxenes and amophous glass. The following were found in the form of insignificant impurities: α-crystobalite, olivine, ilmenite, troilite, spinel (similar to the composition of $MgAl_2O_4$). Table 1 shows the distribution of the minerals on the basis of the data from Moessbauer spectroscopy. Finally, it is very interesting to note that in the rocks of the anorthosite type inclusions of metallic iron of different shapes and sizes are always found. We shall return to this phenomenon somewhat later. Hence, it was found that the regolith from the high-mountain region where the "Luna-20" landed consists primarily of fragments of anorthositic rock, while the mare regolith is composed primarily of basalt type rock. The fine-grain fraction of the regolith ($\leq$ 80 microns) collected by the "Luna-20" /766
is composed primarily of anorthosite with predominance of intermediate ($An_{99.1}$) or nearly (An_{100}) anorthite. While the mare regolith usually contains 1 - 2% anorthosite (the brecchias also contain grains of anorthosite and then the total content will be somewhat higher than approximately 5%), the continental regolith collected by "Luna-20" has an amount of this substance which amounts to 50-60%. Figures 8-10 show the appearance of troctolite, anorthosite from the effusive type and re-crystallized anorthositic glass (apparently a remelted fraction) as they appear under the microscope (80 X).

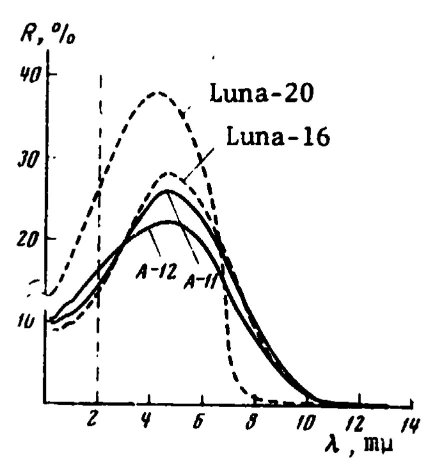

Figure 5. Spectra of Reflection of Regolith from "Luna-16 and 20" and Apollo 11 and 12.

The ferrous minerals in a fine fraction of regolith collected by "Luna-20" are composed of 30% olivine (fine-grained), 50% pyroxene, and only 1% ilmenite, while the mare regolith from Mare Fecunditatis contained up to 10% of the titaniferous mineral, and the mare regolith from Mare Tranquillitatis contained more than 25% of it. Superparamagnetic iron was found in the Moessbauer spectrum.

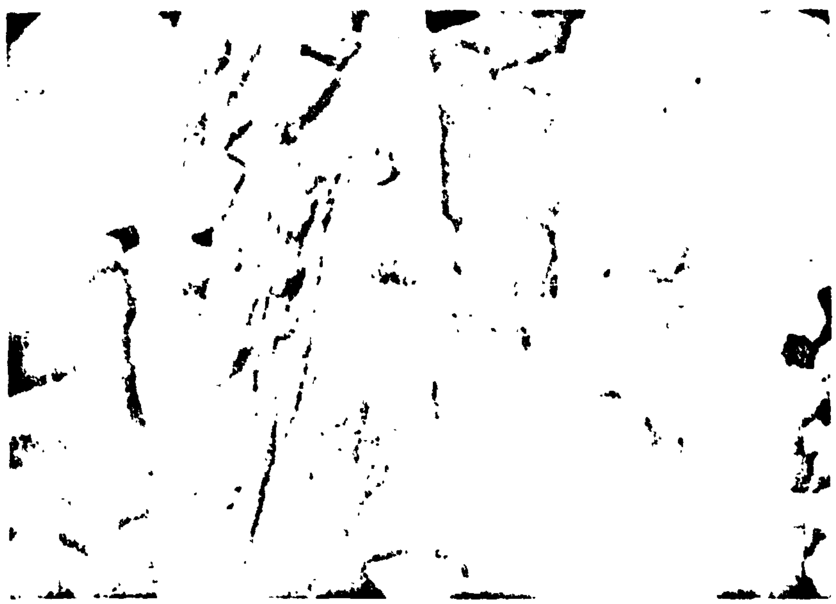

Figure 6. Particle of Regolith Photographed Under a Scanning Electron Microscope. Approximately 7,000 X.

Now let us return to the content of different inclusions of metallic iron in the anorthosite. It is most frequently found in fragments of anorthosite, i.e., associated with crystalline silicates. It seems to me that inclusions of metallic iron in the anorthositic continental regolith are found even more frequently than in the mare regolith. It is true that this requires careful statistics. Metallic iron is found in different forms and is probably of different origin.

Figure 11 shows the inclusion of metallic iron in a particle of finely /767
crystalline anorthosite. X-ray spectral microanalysis of another particle showed the following pattern (Figures 12, a, b, c, d, e, f).

Figures 12 d, e, f show the distributions of aluminum, calcium and silicon. How did this ferrous alloy get inside anorthositic rock? What is this, meteoritic iron? This could explain the patterned appearance of the distribution of metallic iron and silicate-anorthosite in Figure 12 a, b, c.

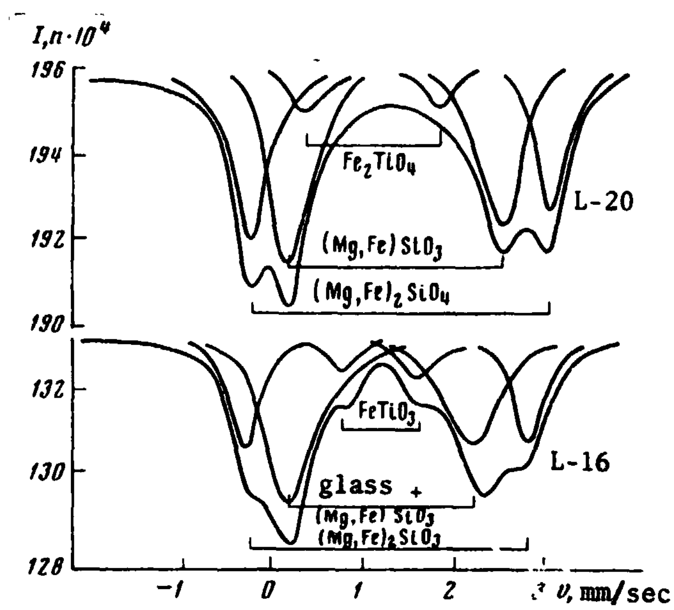

Figure 7. Moessbauer Spectra of Samples of 9-Ip ("Luna-16") and 4-I ("Luna-20") Measured at Room Temperature (Low-Speed Spectrum).

Table 1. Distribution of Minerals (Containing Fe) In a Fine Fraction of Regolith (0.083 mm) in Samples L-16 and L-20.

Minerals	% of Total Area of Moessbauer Spectrum		Wt. % of Total Amount of Minerals	
	L-16	L-20	L-16	L-20
I. nite ($FeTiO_3$)	7.1	≤1.0	1.0	0.05
Ulvospinel (Fe_2TiO_4)	≤1.0	5.8	≤0.06	≤0.9
Pyroxene* ($FeSiO_3$)	71.0	51.0	45.5	40
Glass	- -	-- -	-- -	--
Olivene** (Fe_2SiO_4)	21.9	32.5	3.4	7.8
Iron*** (Metallic)	6.3	12.4	0.33	1.1
Plagioclase	- -	-- -	~50	~50

* Assuming $\frac{FeO}{FeO + MgO} = 20\%$

** Assuming $\frac{FeO}{FeO + MgO} = 40\%$

*** Including fine-granular iron

The bright "nodules" of the Fe-Ni alloy (c, d) were crystallized eariler, and then anorthositic rock crystallized. In fact, experiments which were conducted by us showed the following melting points for lunar rock: /770

"Luna-16"

1. Gabbro - temperature of total melting equals 1235°C (from three determinations).
2. Anorthositic Gabbro - temperature of complete melting equals 1434°C (from three determinations).

"Luna-20"

3. Basalt Rock - temperature of complete melting equals 1070°C (in a narrow temperature range).
4. Anorthositic Basalt - temperature of total melting equals 1170°C (in a narrow temperature range).
5. Anorthositic Rock, Grey - temperature of complete melting equals 1360°C (from two determinations).
6. Single Particle of Anorthite - temperature of complete melting equals 1451°C (from two determinations). Melting begins at 1250-1270°C.
7. Crystalline Anorthosite - temperature of complete melting equals 1384°C (from two determinations).
8. Single Grain of Olivene - temperature of complete melting equals 1342°C.

From the above it follows that the melting point of the silicate components of rocks both in combination (rock) and in the form of single grains does not exceed 1450° which is much less than the melting point of iron or the Fe-Ni alloy. This yeilds a patterned appearance, as we can see from Figure 12a. Figure 13 shows another particle. Its photomicrograph (a) shows the distribution of Fe (b) and Ni (c). The latter figure clearly shows fragments of the iron phase of the meteorite containing kamasite and the brighter area above and to the left is schreibersite. In addition, when using a microscope with high magnification, the field of view in anorthositic rock shows a scattering of fine irregularly shaped pieces of metallic iron, as we can see in Figure 14, (the irregularly shaped white spots). Finally, metallic iron is distributed in the form of the finely-dispersed phase (30-1000 Å) in the surface layer of the particles of regolith, as we can clearly see with the aid of the X-ray electronic method. We first observed this in particles of regolith from Mare Fecunditatis, later from Mare Tranquilitatis, Oceanus Procellarum and finally in the particles of regolith collected by "Luna-20". The maximum density of this ferrous powder can be seen in the particles collected by the "Luna-20". Approximately 50% of the metallic iron in the samples collected by the "Luna-20" are in a finely dispersed state. The most striking fact was that this iron does not oxidize in air at ordinary temperatures. In this dispersed iron from the regolith of the "Luna-20" there is evidently very little nickel or none at all. In contrast to the large particles of metallic iron collected from the regolith of the Mare Fecunditatis, similar metallic iron from the regolith collected by the "Luna-20" contains nickel (> 10%) as can be seen from the Moessbauer spectra in Figure 15. Experience has shown that the dispersed iron is formed as the result of reduction of bivalent iron to metallic iron when basalt is heated to 1500°C in a vacuum (10^{-7}atm). However, it is not oxidized by atmospheric oxygen. From the entire body of data on the nature of the occurrence of iron, it's compounds, alloys, as found in the "Luna-20" regolith, a number of unsolved problems have arisen. Unquestionably, the anorthositic regolith contains fragments of meteoritic alloy. However, it is difficult to explain the occurrence of a ferrous alloy, frequently with a slight nickel content, in the crystalline rocks collected by the "Luna-20". We call attention to the high content of nickel in all the products of the "Luna-20", especially the crystalline fragments (Table 2), which is not the case for crystalline rocks from the mare regolith. It may be necessary to conclude in this instance that these rocks have nothing in common, with the exception of the two pieces of basalt collected by Apollo 14 (mountainous area, Fra Mauro), which also showed a content of about 220 ppm of nickel. One might ask whether this metallic iron might not be /771 a portion of the Moon itself but was brought by meteorites following the final process of accretion of lunar substance.

The "Luna-20" regolith and the fragment of crystalline rock were subjected to X-ray-spectral and mass-spectral analysis, and the results are shown in

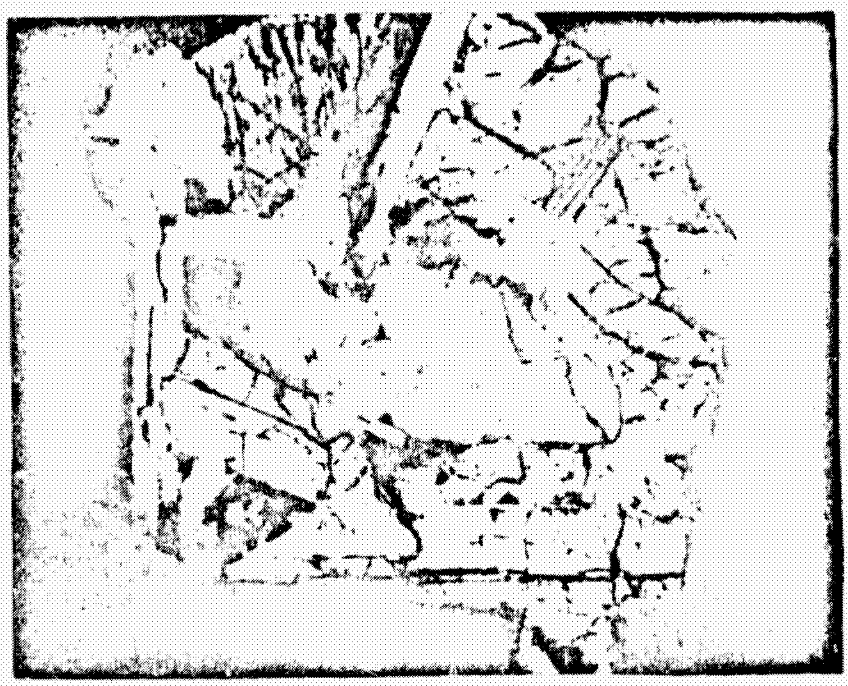

Figure 8. Section of Troctolite in Polarized Light

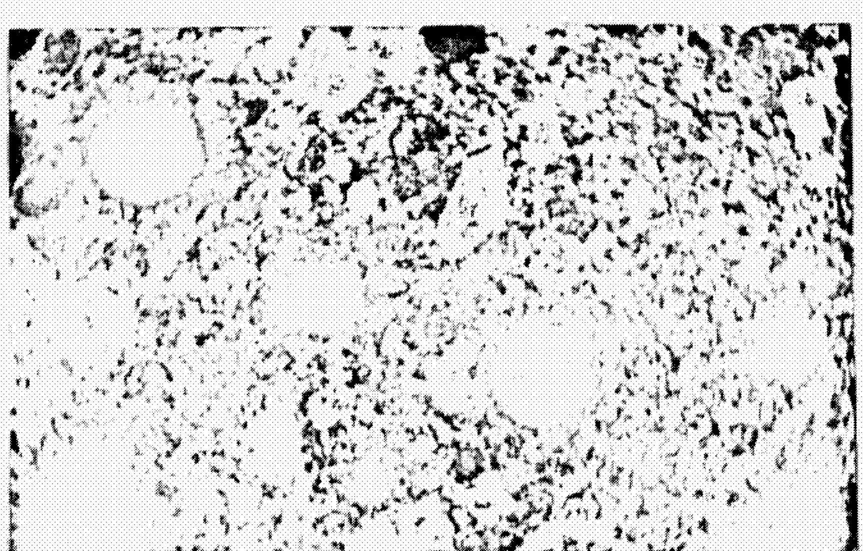

Figure 9. Section of An[illegible]osite with an Effusive Appearance.

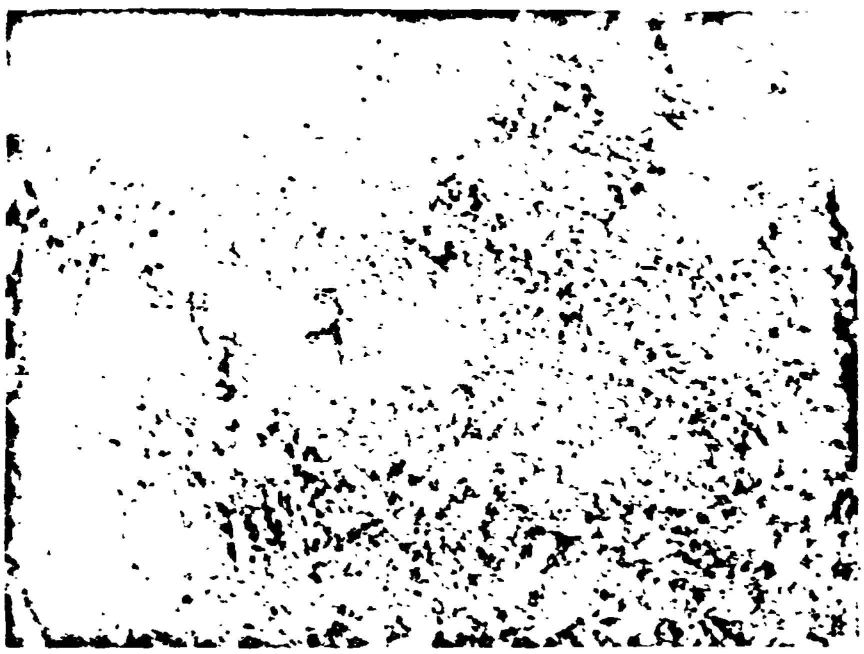

Figure 10. Section of Recrystallized Anorthositic Glass.

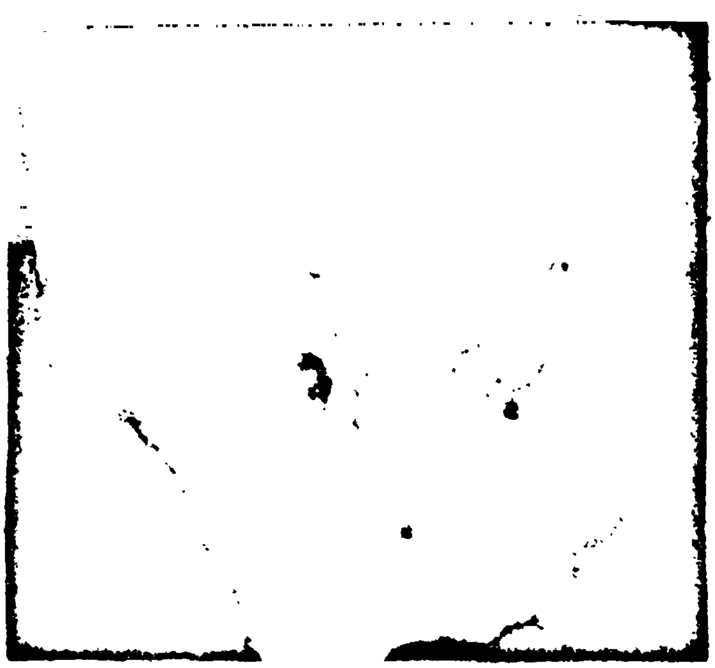

Figure.11. Inclusion of Iron in an Particle of Anorthosite.

a d b e c f

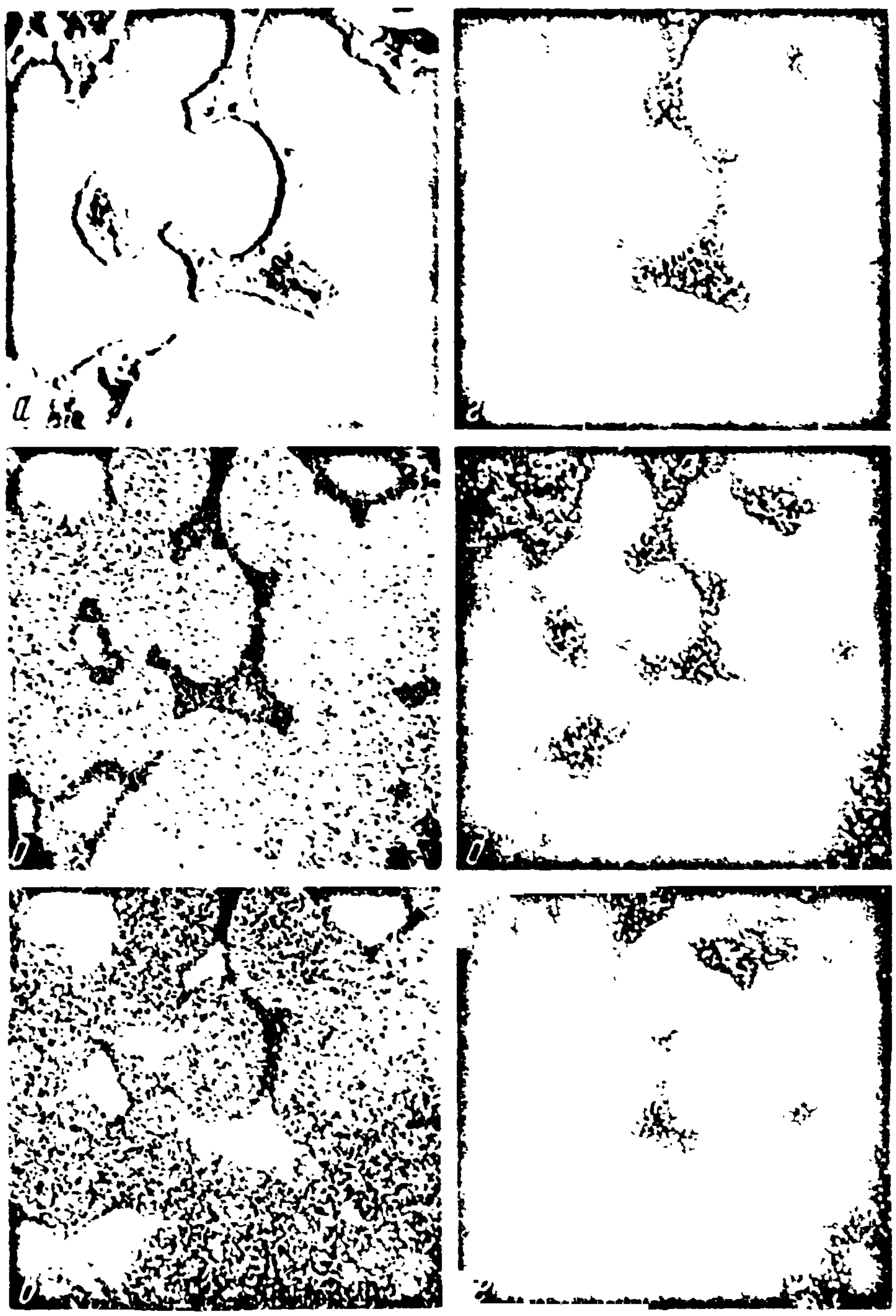

Figure 12. Distribution of Elements Between Metallic and Silicate Phases in a Particle of Metallic Iron on the Basis of Data from X-ray Spectral Microanalysis.

a - distribution in scattered electrons; b - Fe; c - Ni; d - Si; e - Ca; f - mg.

Figure 13. Distribution of Iron and Nickel in a Particle of Metallic Iron on the Basis of Data from X-Ray Spectral Microanalysis.

a - Distribution in scattered electrons

b - Iron c - Nickel

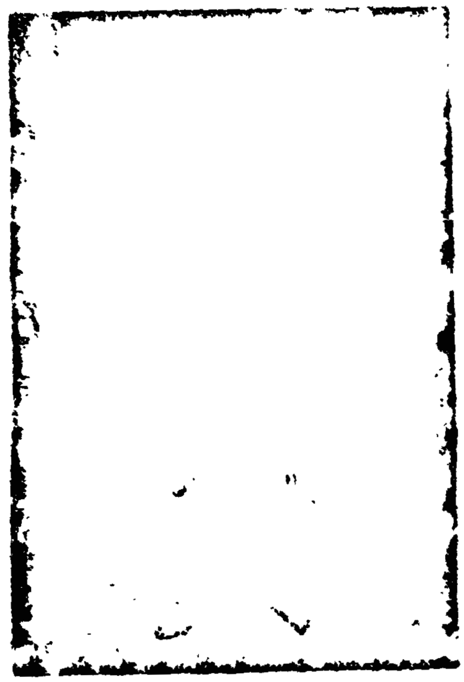

Figure 14. Fine Inclusions of Metallic Iron in Anorthositic Rock in a Polished Section.

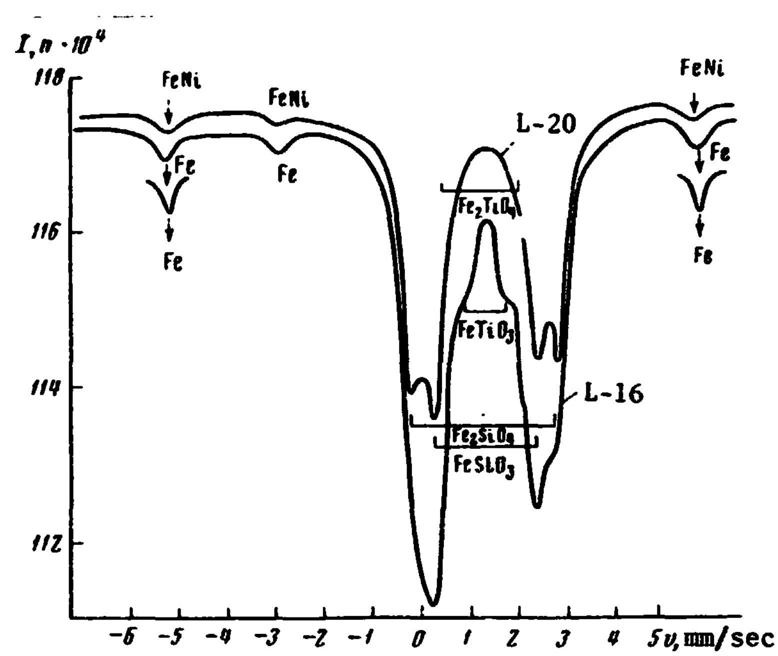

Figure 15. Moessbauer Spectra of Regolith from "Luna-20" and "Luna-16" with a High Speed of the Relative to the Absorber. The peaks of metallic iron are visible. It is clearly evident that the total area of the L-16 peaks is greater than that of the L-20 peaks, due to the high content of iron in the L-16 samples.

Table 2. For comparison, we have also included the data on the composition of the "Luna-16" mare regolith. The fragment of crystalline rock from the "Luna-20" regolith belongs to the rocks of the anorthositic series with a completely crystalline basic mass and phenocrysts of plagioclase and olivene. It is extremely rich in olivene. The continental regolith contains two to three times less FeO and an order less of TiO_2 than the mare regolith and contains considerably more Al_2O_3 and CaO. The Al_2O_3/CaO ratio for the mare regolith is approximately 1.2, while for the continental regolith the Al_2O_3/CaO ratio is about 1.5. The content of Na and K alkalis is slightly higher in the continental regolith. In the initial study of the composition of the regolith, it was rather difficult to determine the deviation of the composition of large

crystalline fragments and the small fraction of the "Luna-20" regolith, since we were unable to determine whether or not there are any kind of changes in the composition of the fine fraction in the course of this process of refinement. In the mare regolith we found a decrease in the content of the mafic elements of Fe, Cr, Mn, V and others, as well as Ti and an increase in the content of Al in comparison with the composition of crystalline rocks. The body of chemical data also supports the fact that the regolith from the "Luna-20" is anorthositic rock which probably consists of a number of analogs of anorthosite, gabbro-anorthosite, anorthositic gabbro, anorthosite-basalt, troctolite, etc. The familiar diversity is also found in the content of certain microelements. The content of certain elements shows only a slight deviation from their content in the mare regolith. For example, Sc, Co, Y, Zr, V and others. We mentioned the Ni content earlier. As we would expect in /773
anorthositic regolith, the content of halides as well as lead and chromium is less than in the mare variety. The latter is very striking in view of the fact that chromium (as we shall see later on) is rarely found in significant quantities in terrestrial anorthosites. There is even less in the anorthositic regolith of the Moon than in the mare regolith of the Moon. The content of TR is considerably less, sometimes a whole order or magnitude less than in the mare regolith. In this case, the TR is the same as the Ca concentration. According to preliminary data, the content of U and Th is low, quite small in comparison with the content of U and Th in the regolith from "Luna-16" and as we know the uranium and thorium content in the regolith from Mare Fecunditatis is smallest in comparison with other maria. In the case of many other chemical elements, orientational data were obtained (Table 2). The tracking method was used to study several crystals of olivene measuring approximately 400 micron from the anorthositic regolith collected by "Luna-20". The tracks are produced by low-energy particles in the form of solar cosmic rays and more precisely by the nuclei of elements of the iron family with energies slightly above 20×10^6 electron volts/nucleon. After etching the samples were studied under the microscope. It was found that in a sample of olivene from "Luna-20" the track density was much less than in olivene from the regolith collected by "Luna-16" by 3-4 orders of magnitude. In the

Table 2. Chemical Composition of Anorthositic Rock and Regolith Collected by the "Luna-20" Automatic Space Station (Macroelements in %, microelements in parts per million. Mass-spectrometric and X-ray spectral data).

Element	Anorthosite (Wt. 60 mg).	Regolith "Luna-20" (Samples 4-1)	Regolith "Luna-20" (Samples 2-1)	Basalt "Luna-16" (Average)*	Regolith "Luna-16" (Average)*
SiO_2	44,2	44,4	45,8	42,95	41,93
Al_2O_3	19,1	22,9	21,6	13,88	15,33
FeO*	6,91	7,03	7,02	20,17	16,66
MgO	13,37	9,70	9,85	6,05	8,78
CaO	13,3	14,2	14,9	10,8	12,53
TiO_2	0,52	0,56	0,53	5,5	3,36
Na_2O	0,48	0,55	0,46	0,23	0,34
K_2O	0,47	0,10	0,10	0,16	0,10
P_2O_5	0,17	0,14	0,17	0,14	0,12
MnO	0,12	0,12	0,13	0,20	0,20
S	0,03	0,08	0,08	0,17	0,21
Sc	36	48	17	31,5	37,2
Co	27	70	53	21,7	41
Ni	189	194	170	79	180
Cu	6,9	27	11	19	37
Zn	6,0	76	39	23,5	33,4
Rb	3,7	1	1	1,3	1,9
Sr	86	230	250	433	253
Y	<110	54	43	90,5	70,4
Mo	2,5	32(?)	27(?)	0,24	5,3
Zr	50	400	230	323	282
Pb	0,15	1,2	0,54	0,33	~4
Ba	66	120	110	238	185
La	—	4,9	4,5	11	13,4
Ce	5,2	1,4	1,2	45	40,8
Pr	1,5	4,5	3,4	10	8,6
Nd	3,1	13	14	32	35,7
Sm	1,5	5,3	3,5	9,7	15
Eu	0,53	0,9	0,74	2,2	2,2
Gd	0,9	2,9	2,5	11	10
Tb	—	0,47	0,52	0,85	1,2
Dy	1,5	4,5	3,9	12	12,5
Ho	0,3	1	0,8	2,8	2,8
Er	0,75	—	1,8	9,6	5,8
Tm	—	0,6	0,27	0,9	0,97
Yb	0,68	1,6	1,6	6,2	5,9
Lu	0,13	0,38	0,28	1,3	1,1
B	2,9	—	39(?)	3,9	4,4
F	107	—	37	128	131
Cl	~12	—	14	29	19,7
Cr	1224	~700	~720	1904	1836
As	~0,2	0,3	0,25	1,5	0,41
Sb	—	<9	<0,2	0,35	0,85
Sn	—	0,8	3	2,3	1,7
In	—	<0,03	<0,4	0,012	0,07
Te	—	—	0,5	—	0,027
Hf	—	4,5	1,6	—	7,8
Cs	-	0,1	0,2	<2	~0,09
Nb	9,3	16	6,8	15	15,9
Br	~0,2	0,27	0,016	0,8	0,5
Se	—	0,7	0,2	0,4	0,36
Ge	0,17	3,5	2,8	1,8	2,25
Ga	3,2	4,5	3,4	3,2	4,5
V	30	70	23	43,8	67,5
Ag	—	1	—	0,053	<0,28
Th	—	~1,5	~0,2	—	0,8
U	—	~0,5	~0,07	—	0,25
Ru	—	—	~0,6	—	<0,10
Os	—	—	—	—	0,03
Ir	—	—	—	—	0,002
Pt	—	—	—	—	0,05
Hg	—	—	—	—	0,14
Rh	—	—	—	—	<0,15
Pd	—	—	—	0,027	<0,38
Li	—	—	—	—	10,8
Cd	—	—	—	0,085	0,52
Tl	—	—	—	—	<0,3
Au	—	—	—	—	~0,0025
Bi	—	—	—	—	<0,2
Be	—	—	—	2,5	—
I	—	—	—	—	0,14

*All forms of Fe are given in the form of FeO

NOTE: Commas equal decimal points

"Luna-16" samples the surface of the olivene (after etching) is covered with tracks with a high density ρ 7×10^7 tracks/cm^2. The samples of olivene from "Luna-20" show only individual tracks with the density of ρ $(3-1) \times 10^4$ tracks/cm^2.

From this it may be concluded that olivene from the regolith collected by "Luna-20" (consequently, all of the rock) was not subjected to such intensive irradiation as the "Luna-16" regolith. In other words, the predominance of anorthositic rock on the surface of the Moon (i.e., it's expositional growth) could not have been very long. The process of formation of anorthosit's, strictly speaking, is unknown. Anorthosites, as we know, are found on Earth, especially in the Archaic (with an age of $3\text{-}3.5 \times 10^9$ years) and in the Proterozoic (with an age of $1\text{-}2 \times 10^9$ years) in the form of massive rocks or stratoform rocks mainly in shields, for example, the Ukriane, Aldan, in Canada, etc. In addition to this, anorthosites appear in regions with pronounced regional metamorphism in association with ultrabasic and basic rocks, in the mantle material of rift valleys. Hence, all of the material of the "Luna-20" regolith as we have seen contains small amounts of mafic elements Fe, V, Mn, etc., as well as Ti, Cr and a great deal of Al and Ca in comparison with the material of the regolith from the mare regions of the Moon. It is particularly necessary to stress the high content of nickel and the much lower amount of chromium in the crystalline fragments than its content in terrestrial anorthosites. The nature of occurrence and distribution of metallic iron in it presents a complicated picture.

The diopside-anorthite state diagram obtained by Yoder is well known. The /774
formation of anorthosite occurs at a temperature of 1095°C at a water vapor pressure of 5,000 bars. However, the formation of anorthosite (anorthite) is possible under waterless conditions at a temperature of 1274°C with a yield of 42 wt.% anorthite. In the usual process of stratification of magma there is a precipitation primarily of crystals of anorthosites and their flotation. Hence, we can assume that the separation of anorthosite in small amounts takes place during the rapid cooling of extrusive high-temperature gabbroid magma and on the Moon it can occur as well under a high vacuum with rapid loss of

volatile substances. The presence of spinels and low-iron olivene is also indicative of crystallization at low pressure and rapid cooling. One is struck by the considerable difference in the melting point and density of the basalts and anorthosites, as we saw earlier. The scale of the formation of anorthositic rocks on the Moon is not very clear. Questions arise as to whether the walls of the calderas of the ringwalls are completely made of anorthosite. It is probable that the age of the anorthositic rocks will be greater than that of the mare basalts inasmuch as the basalts of the lunar maria filled in more ancient territories. All of this calls for new and extensive study. It may be that these problems will be easier to solve on Earth. I do not doubt that following the discovery of rocks of anorthositic type on the Moon (primarily in the mountainous regions) the problem of the origin of anorthosites will attract the attention of terrestrial petrologists.

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